

BULK VAPOR-FORMATION PROCESSES DURING THE ACTION
OF A LASER BEAM ON METALS

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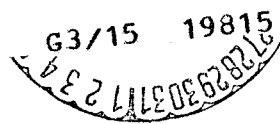
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BULK VAPOR-FORMATION PROCESSES DURING THE ACTION
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ABSTRACT. Analysis of certain problems in the physics of bulk vaporization within surface layers of metal melts heated by laser radiation. It is shown that bulk vapor formation on artificial centers (gas bubbles, inclusions, and dispersed solid particles) leads to supplementary transfer of mass from the beam's zone of action on the metal. The influence of this process on mass transfer from the zone of action is also examined for other sources such as electron beams and a pulsed spark discharge. A71-37586

The fundamentals of the physics of interaction between powerful light radiation and nontransparent materials have been investigated in several theoretical and experimental studies [1 - 5]. The resulting relations make it possible to estimate the depth of the crater formed, and the thickness of the melt film, and the experimental data make it possible to predict the crater shape as a function of the location of the optical system focus relative to the surface of the material being worked. /575*

The possible changes of the optical and thermophysical constants of the materials are accounted for in accordance with the relations of one-dimensional gasdynamics [2], gaskinetics [5], or thermal damage theory [1]. However, we must emphasize that variations of the gas content, impurities, and inclusions in the metals, which do not lead to significant change of the thermophysical and optical properties of the materials, cannot in practice be accounted for in the surface vaporization mechanisms.

*Numbers in the margin indicate the pagination in the original foreign text.

In [2] an estimate was made of the possible role of bulk vaporization in a radiation absorption layer about 10^{-4} cm thick in comparison with purely surface vaporization. The numerical estimates show that for ideal metals (and neglect of gas content, impurities, and inclusions means that the material is ideal in this sense) bulk vaporization in the absorption layer can play an important role in the material damage processes only for temperatures $\sim 0.3 \omega / k$, where ω is the atom bonding energy, k is the Boltzmann constant, i.e., for temperatures of several tens of thousands of degrees. Under ordinary conditions (free generation regime with $q < 10^6 \text{ W/cm}^2$) of laser beam action on the metals the temperature is much lower, and then the role of bulk vaporization becomes very small for ideal materials.

It is clear from physical considerations that ahead of the vaporization front in the material there will be a (two-phase) transition layer of finite thickness. This situation was noted in [6].

In [7] an experimental study was made of the effect of a neodymium laser beam on copper of different degree of purity and gas content. The experimental data show that the crater depth varies with change of the degree of purity and gas content of the copper. Numerical estimates made using the relations of one-dimensional quasi-stationary damage theory yield smaller crater depths /576 than those obtained experimentally, even if we assume complete absorption of the incident radiation, neglecting the reflected portion of the radiation. The possible variation of the thermophysical and optical parameters when changing from one copper grade to another is obviously not great enough to explain the observed difference between the experimental and theoretical values.

Therefore, we have assumed that the damage processes for materials containing internal impurities, inclusions, and gases will take place with participation of bulk vaporization on the artificial nucleate boiling centers of the molten metal. Some aspects of bulk vaporization in the melt zone for relatively low intensities have been considered by the present authors in [8].

In particular, we noted the role of the radiation pulse structure in the mechanism of bulk vaporization development in the melt layer on the metal surface.

In the present paper we examine the role of bulk vaporization in the damage mechanism of nontransparent materials subjected to the action of a laser beam with intensities greater than 10^6 W/cm². The bulk vaporization processes do not have an exact analogy with the boiling processes of nonmetallic liquids. This is associated with the fact that by boiling processes we normally mean all the processes of nuclei formation, bubble growth, and their subsequent emersion. The last stage is absent in metals melted by a laser beam because of the smallness of the bubbles.

I. The boiling process is studied theoretically with the aid of statistical thermodynamics and examination of the equilibrium conditions for the vapor bubbles which form within the liquid or on the surface of the vessel. The temperature at which liquid boiling begins is usually close to the saturation temperature.

In the case of laser beam action in the free generation mode, the external pressure is variable because of the spiking structure of the radiation pulse. As a rule, liquid boiling is due to the presence of vaporization centers in the liquid and on the vessel surface. Nonmetallic liquids can boil in a laser beam, which was apparently first observed in [9].

If there are no artificial vaporization centers, the surface vaporization process plays the dominant role in damage dynamics [2]. For ideal liquids the number I of vapor nuclei formed on the average during the time τ in the bulk of a liquid containing z molecules is determined according to Döring and Folmer [10] by the formula

$$I = z\tau \left[\frac{6\alpha}{(3-b)\pi m} \right]^{1/2} \exp \left(-\frac{L}{kT} \right) \exp \left[\frac{16\pi\alpha^3}{3kT(P_H - P)^2(1 - \gamma/\gamma_s)^2} \right]. \quad (1)$$

where α is the surface tension coefficient, m is the molecular mass, L is the heat of vaporization per molecule, $b = 1 - P/P_H$, P is the pressure in the liquid, P_H is the magnitude of the pressure corresponding to the superheat, γ' is the specific volume of the liquid, γ'' is the specific volume of the vapor at the given temperature T .

Estimates using (1) show that a large nucleus formation rate occurs at very high superheats. Therefore, in actual conditions boiling will take place on the artificial vaporization centers. Before turning to a more detailed examination of the factors leading to the development of bulk vaporization in metal melts, we shall define briefly the conditions under which formation of the liquid phase takes place in a material which is absorbing radiation.

It is known [1, 2] that for a specific absorbed radiation power $q > 10^6 \text{ W/cm}^2$ vaporization processes play the dominant role in the process of energy balance in comparison with thermal conduction. With increase of q the melt zone thickness decreases and quasi-stationary vaporization (in the one-dimensional model) takes place after a short time interval in comparison with the pulse duration. The thickness of the liquid-phase layer (and not the radiation absorption layer as in [2]), where the bulk vaporization processes take place, varies as a function of the magnitude of q from hundreds of microns to a few microns. /577

Figures 1 and 2 show the results of calculation of the melt temperature and melt layer thickness distributions in copper as functions of radiation intensity using the relations of quasi-stationary thermal damage theory for nontransparent materials [11]. The liquid-phase layer thickness is significant for bulk vaporization dynamics, since it is the upper limit of the nuclei critical dimension. An important role in the dynamics of bulk vaporization development is played by the presence of the spiking structure of the radiation pulse in the free generation regime, which leads to pulsations of the melt temperature and propagation of thermal stress waves in the material [8].

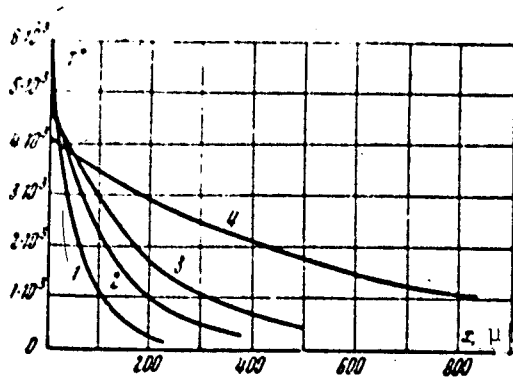


Figure 1. Temperature distribution through melt layer in copper:

$$1 - q = 10^4 \text{ W/cm}^2; 2 - q = 5 \cdot 10^4; 3 - q = 3 \cdot 10^4; 4 - q = 10^5$$

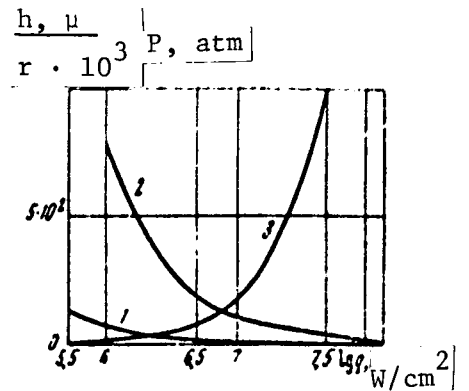


Figure 2. Melt layer thickness in iron (curve 1), copper (curve 2), and the recoil pressure in copper (curve 3) as functions of radiation power density.

It is known [12] that both the mechanical and thermodynamic equilibrium conditions must be satisfied for long bubble lifetime in the liquid. The mechanical equilibrium condition includes the requirements for stability with respect to volume and height. The volumetric stability condition has the form [12]

$$P = P_e + 2\sigma/r, \quad (2)$$

where P_e is the external pressure, P is the pressure in the bubble.

The height stability condition requires that

$$V_b \leq V_c, \quad (3)$$

where V_c is the critical bubble volume.

The thermodynamic equilibrium condition [10] denotes equality of the number of molecules which vaporize into the bubbles and the number of

molecules which condense per unit time. Equilibrium will occur when

$$P = P' \exp\left(-\frac{2\sigma v_l}{kTr^*}\right), \quad (4)$$

where P' is the pressure in the liquid, v_l is the liquid volume per molecule.

Equalities (2) - (4) define the critical bubble radius r^* for which the bubble is in thermodynamic and mechanical equilibrium. In order for the bubbles to grow further, their dimension must exceed r^* .

The artificial bulk vaporization centers will play an important role /578
under conditions of heating by a laser beam with moderate flux densities ($q < 10^8 \text{ W/cm}^2$). Such centers are gas and shrinkage cracks, nonmetallic inclusions, and impurity accumulations. As is known, most nonmetallic inclusions (gases and solid particles — sulfides, carbides, and so on) get into the metal in the melting process itself; the remainder are introduced into the melt with the charge.

According to the ideas presented in [13], finely dispersed solid particles in the metal melt play the role of artificial bulk vaporization centers. Usually, these particles are poorly wetted by the melt and nucleate boiling nuclei can develop easily on their surface. In the case of partial wetting of these particles by the melt, nuclei may develop in the particle microcracks.

It appears that the grain boundaries of polycrystalline materials and twinning boundaries as well do not serve as nucleation centers [14].

In [15] it is assumed that the minimal bubble dimension must be no less than $\sim 0.1 \mu$ in order for it to be possible to carry out macroscopic analysis. Since the thickness of the melt layer adjacent to the surface vaporization front varies from a few microns to hundreds of microns, we obtain the upper

bound of the dimensions of the nonhomogeneities in the metal which can serve as bulk vaporization centers.

The temperature distribution in the laser beam action zone is usually reversed relative to those conditions under which nucleate boiling of liquids is examined in the case of natural convection. At high temperatures the melt motion takes place under the influence of forced convection because of non-uniformity of the recoil pressure at the melt surface, which will lead to agitation of the melt and equalization of the temperature within the volume.

II. Let us examine bubble growth on an artificial vaporization center in a metal melt heated by a focused laser beam. To find the critical dimension of a bubble which is stable in the mechanical equilibrium sense, we write for the moment of time τ the condition analogous to (2) but with account for the presence inside the nucleating bubble of some volume of gas

$$P + \frac{2\alpha}{r} = n \frac{RT}{V} + F(T) = P + \beta/V^{1/3}, \quad (5)$$

where n is the number of gas moles in the bubble ($n \ll 1$)

$$\beta = 2\alpha(4\pi/3)^{1/3}, \quad (6)$$

$$P = P_{at} + P_{rec} + P_h \quad (7)$$

P_{at} is atmospheric pressure, P_{rec} is the pressure due to vaporization from the surface (recoil pressure), P_h is the hydrostatic pressure of the liquid column above the bubble, $F(T)$ is the pressure of the metal vapor in the bubble with account for curvature [16]

$$F(T) = P_0 \exp \left[-\frac{2\alpha}{n_0 k T} \right] \approx n_0 k T \exp \left[-\frac{\omega'}{RT} - \frac{2\alpha}{n_0 k T} \right], \quad (8)$$

P_0 is the pressure at the plane interphase surface, n_0 is the number density

of the melt particles, ω' is the latent molecular heat of vaporization, R is the universal gas constant.

With account for (8) the equilibrium Equation (5) takes the form

$$P + 3/V' = n \cdot RT/V' + n_0 kT \exp \left(-\frac{\omega'}{RT} - \frac{\beta}{n_0 kT V'} \right). \quad (9)$$

The left side of (9) actually depends on the temperature, since the quantity α decreases with temperature increase for most metals.

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For the melt layer thicknesses in question the hydrostatic pressure plays no role, and the recoil pressure can be estimated from the relation [5]

$$P_{\text{rec}} = 1,69qb / \sqrt{L}(1 + 2,2b^2), \quad (10)$$

where $b = kT_0/mL$, m is the molecular mass, T_0 is the surface temperature for quasi-stationary vaporization.

Figure 2 shows the results of recoil pressure calculations using (10) for copper for various values of q .

Estimates of the critical values of V at which bubble equilibrium is possible for a given temperature show that the terms due to Laplacian gas pressure in the bubble play the dominant role in (10). The critical bubble dimension for copper with $q = 10^6 - 10^7 \text{ W/cm}^2$ is $10^{-5} - 10^{-6} \text{ cm}$. It is obvious that such large bubbles cannot be formed by the fluctuation technique (for the given temperature of $\sim 4 \cdot 10^3$ degrees).

Using (9) and the relation for the temperature distribution through the melt layer, which for quasi-stationary vaporization has the form [11, 17]

$$T = T_0 \exp(-vx/a), \quad (11)$$

where v is the vaporization rate and a is the thermal diffusivity coefficient, we can estimate the dimensions of bubbles which are in equilibrium with respect to volume (for the given temperature) and thereby find the lower bound of the depth of the melt film involved with bulk vaporization on artificial centers. Specifically, for copper with $q = 10^6$ W/cm² the lower bound corresponds for the equilibrium bubble to a temperature $T \cong 3,5 \cdot 10^3$ degrees, which corresponds to a depth of 50 μ , and is two orders of magnitude greater than the absorption layer thickness.

Now let us examine the growth dynamics of a supercritical bubble under conditions of laser beam heating. Bubble growth takes place under conditions of increasing heat transfer to the bubble boundary in the course of time because of surface vaporization (bubble motion opposite the vaporization boundary in the coordinate system fixed with the vaporization front). The bubble growth equation was formulated by Rayleigh [18] (for cavitation) and has been analyzed in [19 - 21]. According to these studies, bubble growth in the bulk of a uniformly heated liquid is proportional to $\sqrt{\tau}$ /580

$$r(\tau) = A \cdot 2c_p \gamma' \Delta T (\pi a \tau)^{1/2} / \pi L \gamma'', \quad (12)$$

where A is a constant, equal to $\sqrt{3}$ [19], $\pi/2$ [20], $\sqrt{\pi}$ [21]; c_p is the specific heat, ΔT is the superheat.

Account for the high thermal conductivity of the molten metals in comparison with the nonmetallic liquids leads to the following expression [22]

$$r(\tau) = A \cdot \frac{2}{\pi} \cdot \frac{c_p \gamma' \Delta T}{L \gamma''} \left[(\pi a \tau)^{1/2} + \frac{A \lambda}{\alpha_\phi} \ln \frac{A \lambda / \alpha_\phi}{A \lambda / \alpha_\phi + (\pi a \tau)^{1/2}} \right]. \quad (13)$$

where α_ϕ is the heat transfer coefficient with phase transition, λ is the thermal conductivity of the melt.

Numerical calculations using (12) and (13) for a copper melt lead to the following results. The lifetime of an individual bubble in the melt is determined by its location depth (ignoring convection) and the specific radiation power, which determines for a given material the stationary surface vaporization rate. Moreover, we assume that because of the smallness of the growing bubbles, their emersion velocity is low [8]. The location depth of the nucleating bubble for which the growth initiation conditions are satisfied also depends on the specific radiation power.

A curve of bubble lifetime versus specific power for copper is shown in Figure 3. In the calculation account was taken for increase of the vaporization rate and contraction of the melt zone with increase of q .

Figure 4 shows the results of numerical calculations of the dependence of the bubble radius in a copper melt on the specific power up to the moment corresponding to the lifetime duration of an individual bubble. In the calculations we assumed that the superheat was 1.05 and 0.2 degrees (curves 1, 2, and 3 respectively).

We see from the calculation results that by the time the bubble reaches the vaporization surface its dimension for a superheat of 1 degree is close to the melt zone thickness corresponding to the given radiation intensity. These results make it possible to estimate the maximal dimensions of liquid metal droplets which can be removed as a result of the action of a pulse applied to the liquid volume during bubble growth. The maximal size of the liquid metal droplets which are carried away as a result of bubble growth decreases with increase of the specific radiation power. This conclusion is valid for the initial stages of the process, when a cavity has not yet formed in the metal. In the later stages of the process, removal of droplets which

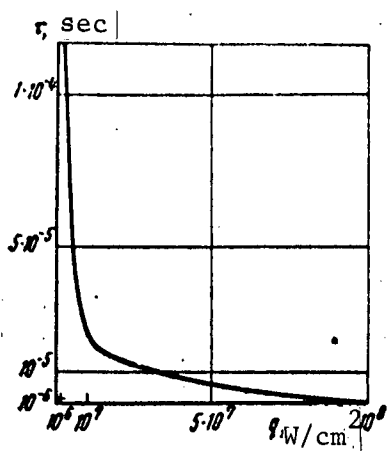


Figure 3. Bubble lifetime (in copper melt) versus specific radiation power.

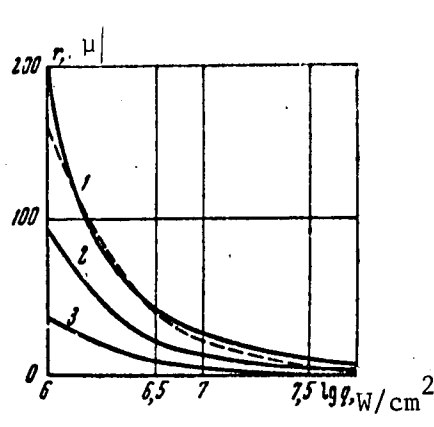


Figure 4. Bubble radius in copper versus specific radiation power (calculations carried out up to instant corresponding to bubble lifetime duration).

Superheat equal to 1°C (curve 1), 0.5°C (curve 2), 0.2°C (curve 3). Dashed curve is melt thickness versus q for copper.

are larger than the melt layer thickness may be due to the processes of melting and elution of the liquid film from the side surface of the crater [1, 23].

Under experimental conditions it is obviously possible to observe separately the liquid-phase droplets removed as a result of the bulk vaporization processes and as a result of the melting-elution processes. This is associated with the fact that for the second process droplet scattering will take place basically at some angle to the zone-of-action surface, while for the bulk vaporization processes droplet scattering will also take place along the normal to the melt surface. Droplet scattering along the normal to the melt surface is actually observed experimentally (see, for example, [24]).

The bulk vaporization processes have an influence on the damage mechanism through the temperature distribution in the liquid layer adjacent to the vaporization boundary. Figure 5 shows the calculated liquid layer thickness,

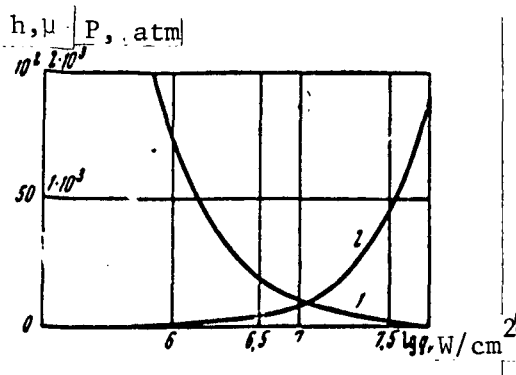


Figure 5. Liquid layer thickness (curve 1) and recoil pressure (curve 2) for iron versus specific radiation power.

stationary vaporization rate, and recoil pressure as functions of radiation power density for iron ($t_m = 1530^\circ \text{C}$, $\lambda = 0.15 \text{ cal/cm} \cdot \text{sec} \cdot \text{deg}$, $L = 1630 \text{ cal/g}$). We see from Figure 5 that for iron the conditions for bulk vaporization on artificial centers are more favorable in comparison with copper, since the recoil pressure on the liquid phase in equivalent thicknesses of the liquid phase is lower than for copper. This circumstance increases the number of supercritical

bubbles for a given melt depth. Therefore, the influence of the bulk vaporization processes on the crater depth in iron will be more marked.

The artificial vaporization center distribution in real materials must have a statistical nature. Therefore, the distribution of the material removed by bulk boiling must also have a random nature in time and space. This conclusion is in agreement with experimental data on the angular distribution of material (thallium) vaporized by a laser beam [24], since the observed angular distribution of the β -active thallium isotope Tl^{204} has a statistical nature for both the free-generation and Q-switched regimes.

Let us examine qualitatively the influence of the bulk vaporization processes on the damage zone with further contraction of the pulse duration (transition to the Q-switched regime). Increase of the radiation specific power and shortening of the pulse duration lead to decrease of the thickness of the melt zone adjacent to the vaporization surface, increase of the temperature in the narrow layer (the absorption layer in the limit) to temperatures above the critical value, and decrease of the nucleating bubble lifetime. Transition to such conditions means that the artificial vaporization centers

do not play a noticeable role in comparison with the spontaneous centers, since the material in the absorption layer can be considered a high-density gas [2, 25]. Therefore, the case of pulse duration decrease while maintaining the magnitude of the radiation intensity at the level $q < 10^8 - 10^9 \text{ W/cm}^2$ is of interest for our present investigation. Calculations for copper (Figure 3) show that for a specific power of 10^8 W/cm^2 the individual bubble lifetime amounts to $3 \cdot 10^{-7}$ seconds, in the course of which the bubble can grow from the nucleating dimensions to dimensions comparable with the melt zone thickness (of the order of a few microns). Therefore, if we assume that the heat input mechanism to the bubble boundary remains the same, the bulk vaporization role remains unchanged in these conditions as well, although its role in the material removal mechanism will be reduced (the pulse duration is less than the bubble lifetime).

In conclusion we should emphasize that study of the bulk vaporization processes on artificial centers can yield additional information on the mechanism of light radiation interaction with real materials. Moreover, the phenomena examined in the present article can also take place under the action of other concentrated energy sources on solid bodies. Such sources include the action of a focused electron beam and a pulsed electrical discharge. In this case, the bulk vaporization phenomena develop in larger regions within the volume of the material, since the heat sources in this case are three-dimensional. Facilitation of ebullition (with increasing role of spontaneous nuclei) of a region can be observed at times corresponding to termination of the pulse action, i.e., when the recoil pressure is relieved at a time when the melt has not yet cooled in the volume in comparison with the surface. This will lead to explosive removal of material from the melt zone after a time interval which is termed the energy-buildup time [26 - 28] and will be accompanied by scattering of the metal.

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REFERENCES

1. Anisimov, S.I., Ya.A. Imas, G.S. Romanov and Yu.V. Khodyko. *Deystviye Izlucheniya Bol'shoy Moshchnosti na Metally* (Action of High-Power Radiation on Metals), Nauka Press, 1970.
2. Afanas'yev, Yu.V. and O.N. Krokhin. *Zh. eksperim. i teor. fiz.*, Vol. 52, No. 4, 1967, p. 967.
3. Ready, J.F. *J. Appl. Phys.*, Vol. 36, No. 2, 1965, p. 462.
4. Bonch-Bruevich, A.M. and Ya.A. Imas. *Fizika i khimiya obr. mater.*, No. 5, 1967, p. 3.
5. Anisimov, S.I. *Zh. eksperim. i teor. fiz.*, Vol. 54, No. 1, 1968.
6. Nemchinov, I.V. *PMM*, No. 10, 1967, p. 210.
7. Brekhovskikh, V.F., N.N. Rykalin and A.A. Uglov. *Dokl. AN SSSR*, Vol. 190, No. 5, 1970.
8. Rykalin, N.N. and A.A. Uglov. *Fizika i khimiya obr. materialov*, No. 2, 1970, p. 33.
9. Askar'yan, G.A., A.M. Prokhorov, G.F. Chanturiya and G.P. Shipulo. *Zh. Eksperim. i teor. fiz.*, Vol. 44, No. 6, 1963.
10. Nesis, Ye.I. *Usp. fiz. nauk*, Vol. 87, 1965, p. 615.
11. Anisimov, S.I. *Teplofizika vysokikh temperatur*, Vol. 6, No. 1, 1968.
12. *Kurs Fiziki* (Physics Course). (Edited by N.D. Papaleksi), Moscow-Leningrad, Gostekhizdat, 1947.
13. Frenkel', Ya.I. *Kineticheskaya Teoriya Zhidkosti* (Kinetic Theory of Liquids), Izdstel'stvo AN SSSR, 1945.
14. Clark, H.B., P.S. Streng and J.W. Westwater. In the collection: *Physics of Boiling* (edited by I.T. Alad'yev), Mir Press, 1964.
15. Hirth, J.P. and G.M. Pound. *Vaporization and Condensation*, Metallurgiya, 1966.

16. Landau, L.D. and E.M. Lifshits. Statisticheskaya Fizika (Statistical Physics), Nauka Press, 1964.
17. Makarov, N.I., N.N. Rykalin and A.A. Uglov. Fizika i khimiya obr. materialov, No. 1, 1969, p. 23.
18. Rayleigh, Phil. Mag., Vol. 346, 1917, p. 94.
19. Plesset, M.S. and S.A. Zwick. In the collection: Physics of Boiling (edited by I.T. Alad'yev), Mir, 1964.
20. Forster, H.K.E. and N. Zuber. In the collection: Physics of Boiling (edited by I.T. Alad'yev), Mir, 1964.
21. Labuntsov, D.A. Inzh.-fiz. zhurn., No. 4, 1963.
22. Subbotin, V.I., D.N. Sorokin, D.M. Ovechkin and A.P. Kudryavtsev. Teploobmen pri Kipenii Metallov v Usloviyakh Yestestvennoy Konveksii (Heat Exchange During Boiling of Metals Under Conditions of Natural Convection), Nauka Press, 1969.
23. Ulyakov, P.I. Zh. eksperim. i teor. fiziki, Vol. 52, No. 4, 1967.
24. Bykovskiy, Yu.A., A.G. Dudoladov, N.N. Degtyarenko, V.F. Elesin, Yu.P. Kozyrev and I.N. Nikolayev. Zh. eksperim. i teor. fiziki, Vol. 56, No. 6, 1969.
25. Afanas'yev, Yu.V., V.M. Krol', O.N. Krokhin and I.V. Nemchinov. PMM, Vol. 30, No. 5, 1966.
26. Zuyev, I.V., N.N. Rykalin and A.A. Uglov. Fizika i khimiya obr. materialov, No. 5, 1968, p. 7.
27. Zuyev, I.V., N.I. Rykalin and A.A. Uglov. Fizika i khimiya obr. materialov, No. 3, 1970.
28. Goloveyko, A.G. Izvestiya Vuzov, Energetika, No. 6, 1966.

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